# Understanding Arctic Ice

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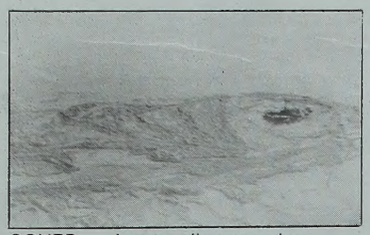


*COVER — A naturally occurring ice field around Isserk Island on the Canadian side of the Beaufort Sea.*

# Understanding Arctic Ice

*America's oil industry in the 1980s faces unprecedented challenges in finding and developing new reserves of oil and gas at home. Many of our future discoveries will require extensions of current technology, and will be located in areas that are more hostile and remote than ever before. These new reserves are needed to reduce the nation's increasing dependence on foreign supplies of petroleum.* Interruptable *supplies. This disquieting fact was twice made painfully real to Americans in the decade of the '70's.*

*But our country's oil companies must also carry out their job in a manner consistent with a need to protect the environment.*

*This dual charge is taken with highest concern in frontier areas such as the Alaskan arctic, where the potential for oil discoveries is perhaps greatest. Exxon is committed to working safely and in harmony with nature, and with the region's native Alaskans—the Inupiat Eskimos, whose culture has existed in this harsh area for centuries.*

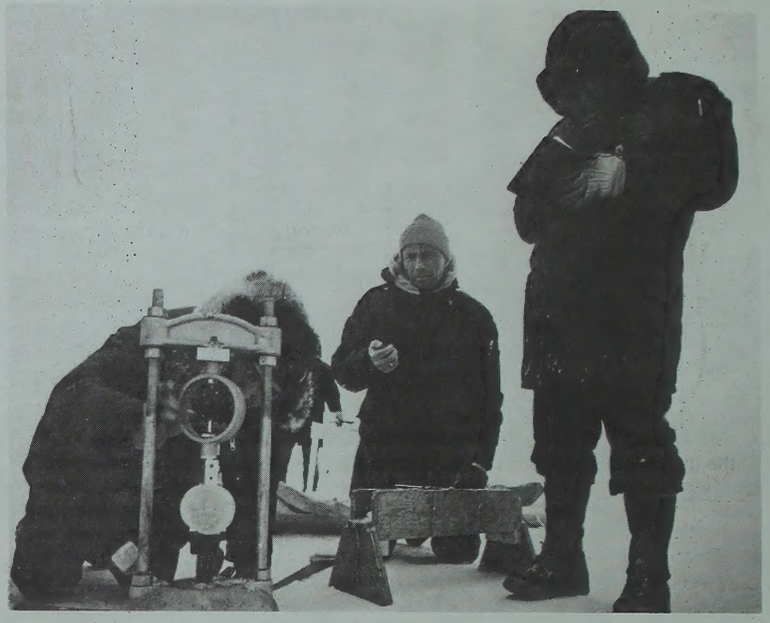
*The December 1979 Beaufort Sea oil and gas lease sale set the stage for a dramatic new program of offshore exploration. Yet even at a time of new beginnings, Exxon is no stranger to the terrain or climate of the arctic. Since 1968, it has supported an intensive scientific study of the arctic in general, and sea ice in particular.*

*The full-time attention of many dozens of scientists, engineers, and technicians, representing a variety of academic disciplines, has focused on the subject of arctic ice and arctic oceanography. Field studies have supplemented laboratory work. The result is a large reservoir of scientific data and a growing understanding of the structure of ice, its formation, and its behavior —under almost every conceivable condition.*

*The subjects of sea ice dynamics, arctic oceanography, and meteorology all have been developed at a cost of many millions of dollars. So have the earth sciences as they relate to the sea bottom and subsea permafrost, as well as the marine biology, microbiology, and zoology of the Beaufort Sea.*

*This advanced research is being applied by the engineering professionals who have the task of designing the various structures and support systems required for arctic oil and gas exploration and production. Those specialists now have the knowledge needed to permit such work to be carried out with maximum protection for both the people and the environment of the Beaufort.*

EXXON COMPANY, U.S.A.



*Ice researchers accompanying the S.S.* Manhattan.

# Break Through

A strange, almost uncanny, coincidence of historic events took place in the summer of 1969. On July 20, American astronauts accomplished the almost unbelievable: a landing on the moon. The attention of the whole world focused on the earth's lifeless satellite as the space travelers stepped from their craft for the first time.

Far overshadowed by that awesome achievement was another historic first that year. It took place here on earth, in a region which, in some ways, was almost as desolate and forbidding as the moon. This was the first successful crossing of the arctic ice pack by a commercial ship. It was achieved September 4, 1969, by the ice-breaking tanker SS *Manhattan.*

The crew—Captain Roger Steward and men of the Exxon marine fleet—had accomplished what commercial seamen for five centuries had failed to do: they had traveled the Northwest Passage, the almost mythical marine route across the top of the North American continent.

The voyage of the *Manhattan* was, however, considerably more than a deed of high adventure. It was a scientific expedition, designed to determine the economic feasibility of shipping crude oil by tanker from the newly discovered Prudhoe Bay oil field on Alaska's arctic coast to refineries in the eastern United States.

Before that could be attempted on a regular basis, the long-dreaded arctic ice pack had to be conquered. That required individual courage and technical expertise; and, more importantly, scientific information about the ice never before available.

To gather this vital information, teams of scientists became part of the ship's complement. Daily they left the ship and ranged across the ice—on foot, by snowmobile, or by helicopter. The scientists and their technicians measured the ice's thickness; and, in their shipboard laboratories, determined its age, strength, chemical composition, and crystallographic structure.

The voyage of the *Manhattan* marked the second year of intensive and ongoing study of arctic ice by Exxon. It was a commitment begun in 1968—at the time of the Prudhoe Bay discovery. Ultimately, it would have benefits far beyond that of permitting the regular movements of ships through ice-choked waters.

In the decade that followed, U.S. and Canadian oil companies would receive authority to explore for oil and gas in the waters of the Beaufort Sea—that portion of the Arctic Ocean off the northernmost coast of Alaska as well as Canada's Yukon and Northwest Territories. To permit that work to be done with maximum safety, oil industry scientists would set out to learn more than ever before about ice in the Beaufort.

At their disposal were the most advanced research tools available. These permitted the researchers to examine in a new way this powerful element of nature—this force that had tyrannically ruled, and at times had destroyed, dwellers and explorers of the Northland. The Inupiat Eskimos of Northern Alaska had long ago discovered methods that they believed could predict ice movements even before they occured. Even so, theirs was exclusively a knowledge of the ice's surface. Now scientists were able to profile its depths.

To do this, laser beams were transmitted down from surveillance aircraft. At the same time, airborne infrared cameras recorded images that allowed analysts to establish the age of the ice. Underwater television cameras and conventional underwater photography probed the sea bottom and the underside of the ice. Sonar and side-looking radar, infrared scanners, laser profilometers—all these instruments were employed to amass data.

Among the early findings of ice scientists were some that seemed so obvious that one might wonder why they needed research: there is ice that is *new*—that is, formed in the current year; and ice that is *old*, formed more than a year ago. This may seem, even to a layman, to go without saying. But the difference is significant, as we will see later. It is part of an investigation into the physical strength of sea ice; strength determined not only by temperature but also by age, salt content, density, and crystal structure, all of which vary throughout the ice.

The scientists also gave ice other labels—*rotten*: about to melt, *dirty*: high in sediment, *clean*: not carrying sediment. These easily-understood conditions were found to affect the characteristics of the ice in ways that were not immediately apparent.

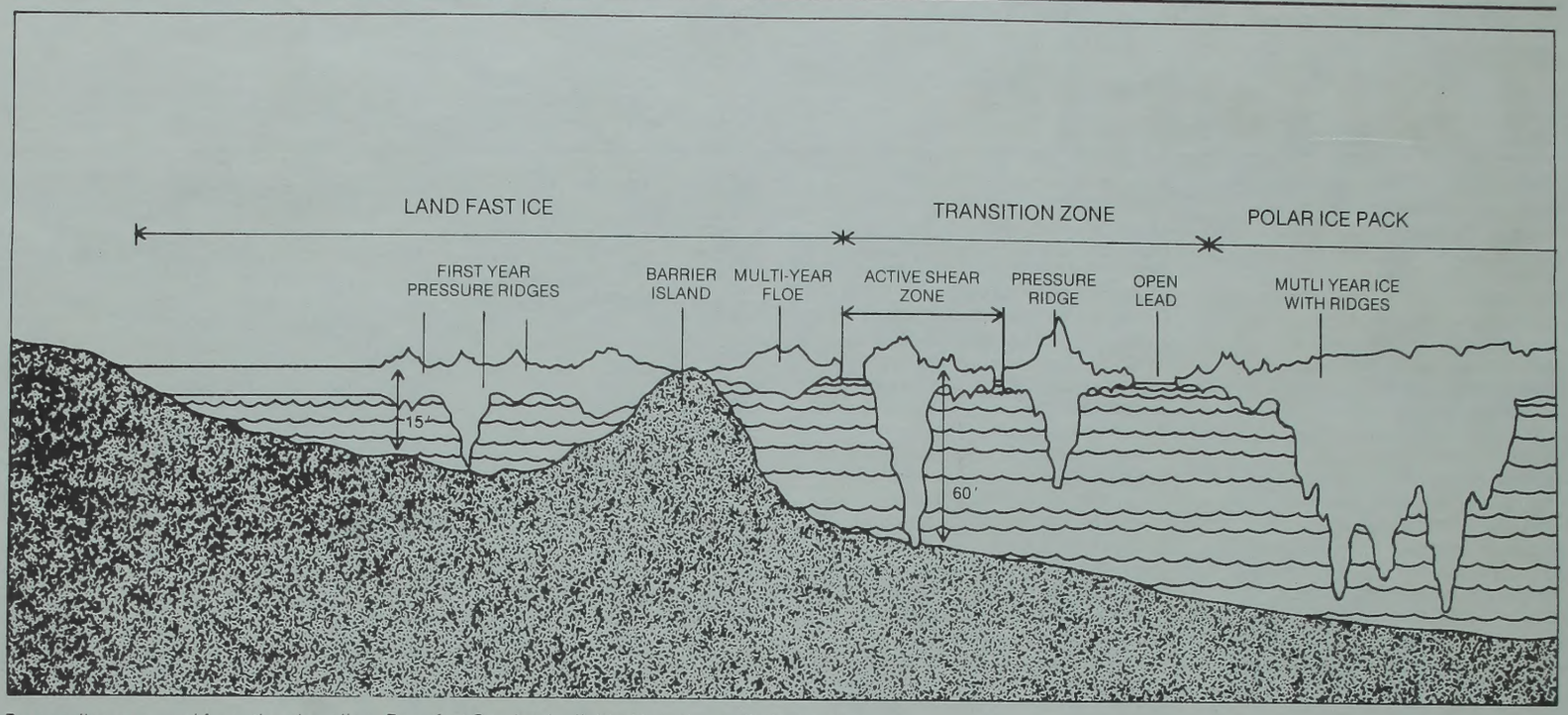
Throughout the decade of the 70's the research continued to expand. Specialists were brought in from universities, from the governments of Canada and the U.S., and from private research foundations. From the time of the *Manhattan* expedition in 1969, the price tag for joint research by the American oil industry amounted to $61 million. Individual companies funded additional research over and above this amount.

*The* Manhattan *Voyage: Careful planning preceded its success.*

Together these efforts produced a wealth of information that took knowledge of sea ice far beyond the limits once imposed by the isolation and extreme climate above the Arctic Circle. Instead of finding himself a helpless witness before the shifting ice floes, man has become an investigator—monitoring ice movements, tracking direction, measuring pressure changes, and then, as necessary, taking action to minimize the threat posed by those conditions.

Never before in history has this been possible. Such control opened up a new era for productive work in the arctic.

# Defining The Zones




*Proceeding seaward from the shoreline, Beaufort Sea ice is divided into three distinct zones.*

There are a number of stereotypes about the "frozen north" commonly held by people who do not live there. The research of the '70s clearly demonstrated that many of them simply aren't true. For one, the Arctic Ocean isn't always frozen. Even in the dead of winter, in the thickest part of the pack, ice can break and open up channels to the water below. In most summers, the ice along the shoreline melts almost entirely.

The ice is also anything but stationary—despite its appearance in picture postcards of the arctic. It is driven by winds, and swept by tides and currents. Under such conditions, it can begin to move steadily. Great ridges may form, and one sheet may abruptly ride up on another. Such startling phenomena led to a widely held belief that once the ice starts moving, nothing can stop it. Not until the advances of the past decade were scientists able to demonstrate that this was not always true.

Research showed that ice characteristics—and thus ice behavior—vary in different parts of the Arctic. Sea ice can be divided into a series of clearly defined zones, proceeding seaward from the shoreline. The area of the Beaufort Sea closest to the shore, for example, is a region characterized mainly by the so-called *landfast* or *shorefast* ice. The term has nothing to do with speed, but the fact that, as autumn temperatures drop, the newly-formed ice attaches itself to the shoreline and remains held fast while formation then progresses seaward. This process usually begins in mid-October.

This ice forms in a relatively narrow band that extends out to water depths as great as 60 feet—anywhere from three to 15 miles from the shoreline. Landfast ice is a continuous sheet of relatively smooth first-year ice, anchored to the coast and also to the shallow sea floor to a depth of about six feet by winter's end. It is relatively stable in terms of movement.

Still, there are times of movement at all locations. Early in the winter—usually through November and December, before it has reached its maximum thickness—the relatively thin ice sheet can be moved by winds, causing it to form ridges. Offshore winds may also open up breaks in the still-forming sheet, resulting in stretches of open water known as *leads* or *channels*.

As winter progresses into January and February, the landfast ice becomes relatively stable, although movement of tens of feet can still occur owing to the influence of winds, or to temperature changes that cause thermal strains. In shallower waters, there can also be even smaller movements, called *creep* or *ductile deformation*. At times, where the slope of the beach is gentle and no protective measures are applied, the ice will push up onto the shoreline.

Beyond the landfast ice, proceeding offshore, is the *transition zone*. It is approximately 10 to 100 miles wide. This zone is composed of both new and old ice, in constant motion. Because the ice at times breaks into drifts, only to be frozen and refrozen into new relationships, the surface of this zone is marked by heavy ridges and highly irregular features. Its undersurface also is irregular. Upended ice-forms protrude into the sea floor.

The landward edge of the transition zone is a highly deformed area, known as an *active shear zone*. Typically a few hundred feet to several miles wide, this active shear zone is caused by the grinding action between the relatively stable landfast ice and the moving ice in the transition zone.

Almost any type of ice movement is capable of causing pressures, and thus of deforming the ice. The transition zone is a jumble of these ice actions, all brought together in one place in a kind of ice researcher's archive: ice pans, floebergs, thermal cracks, rubble piles, open leads, frozen leads, pressure ridges, hummocks, ice floes, ice islands—and more. From the air, each of these deformations has recognizable surface features. And to the trained eye, each has distinguishable characteristics.

The *ice pan*, for example, has a distinctive rounded shape and a pan-like lip at its edge. It is formed when pieces of an ice sheet break apart and grind against one another.

The ice pan is readily distinguishable from the *ice island*—another example—even though both have generally flat upper surfaces. Originally part of an ice shelf, the ice island is composed not of sea ice, but at least partially of glacier ice that has broken off and drifted to sea. Among other things, the ice island rides much higher in the water—an indication of its greater thickness, and its greater mass below the waterline.

Beyond the transition zone is the *polar ice pack*. This is the greatest of the zones—extending seaward from the transition zone to the North Pole and beyond. From October to June the Arctic Ocean remains virtually ice-locked in this vast pack. Yet there is unceasing movement. Under the influence of winds, ocean currents, and the rotation of the earth, the arctic ice pack slowly drifts in a clockwise pattern. This great mass makes one complete revolution about every three years.

# From The Cold Room

While field research and aerial surveillance continued in the 70's, laboratory investigation of sea ice was being carried out by Exxon affiliates in Canada and in Houston, Texas. There, researchers used a "cold room" in order to test the properties of Beaufort Sea ice samples under controlled conditions.

Esso Resources Canada, Ltd. in Calgary, Alberta is also the site of the world's largest ice testing basin. The basin permitted experts to create such Beaufort Sea phenomena as moving ice sheets and ice rubble fields. Through photography and instrumentation, the scientists routinely studied the ways in which moving ice affects the types of structures to be used in arctic oil and gas exploration.

At the same time, other laboratory researchers were slicing ice into wafer-thin sections to study its crystalline structure. This information is directly related to the strength characteristics of Beaufort Sea ice.

It is a well-known fact, for example, that salt is not incorporated directly into the solid crystal structure of ice. Instead, it is captured in small inclusions of high salinity in the ice. These are called *brine pockets*. In time, the trapped salt is forced downward from the ice's surface, draining primarily through a series of vertical tubes called *brine channels*.

As the ice grows through the fall, part of the brine slowly migrates downward—*"leaches"*—out of the ice sheet. A clearly defined process of brine drainage continues throughout the year. Any ice which survives the summer will have its salt largely flushed away. This "old" or multi-year ice is amost entirely fresh and—of particular importance to engineers who must design structures to operate in the arctic—it may be stronger than first-year ice, and is usually thicker.

*Pressure testing a Beaufort Sea ice sample. Ice strength depends on, among other things, the length of time that pressure is applied.*

Equally important is the crystal structure of the ice. A typical ice sheet can actually be composed of several distinct zones. The upper zone of normal sea ice may be composed of very fine crystals. Below this are elongated crystals. And below this, the crystals become significantly lengthened in the up-and-down direction, which is referred to as the *columnar zone*.

All this is of importance to engineers. Laboratory stress tests have shown that very fine crystals are more than twice as strong as elongated crystals. The engineers also have found that the orientation of the crystals causes the strength of ice to vary. For example, if the individual crystals are aligned horizontally to the direction of a force, this tends to increase the crushing strength of the ice.

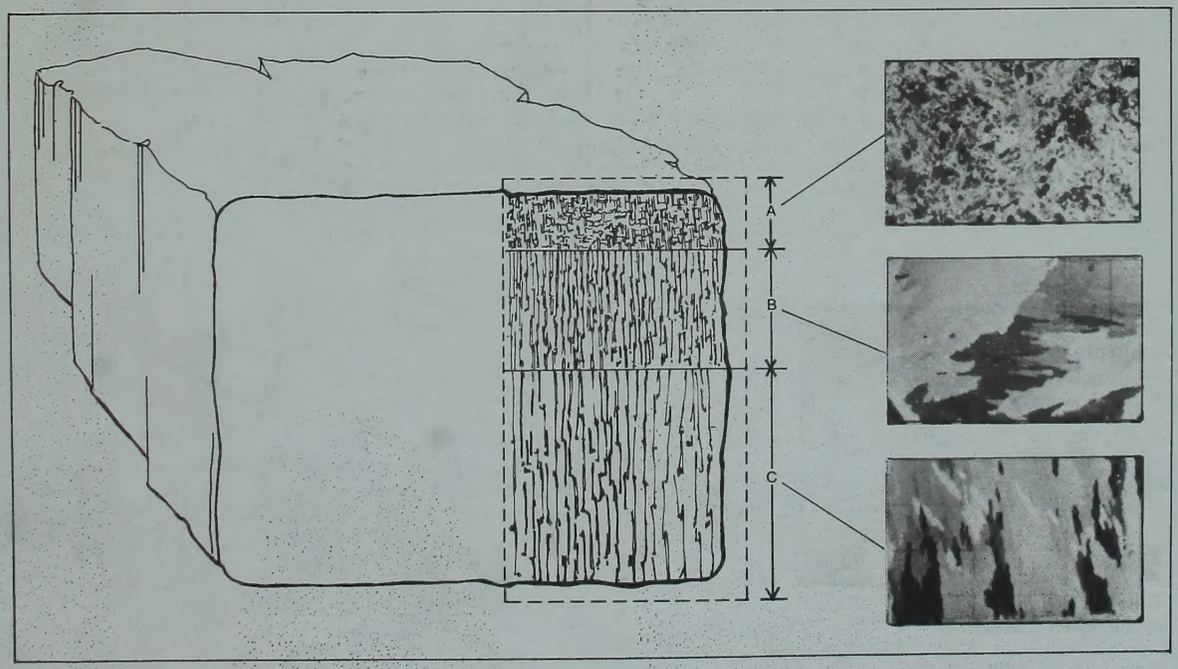
Yet, quite apart from physical composition, the ultimate strength of sea ice is also affected by another, possibly unexpected factor—*time*. For example, an aircraft landing on an ice runway will produce a rapid bending of the ice, which bounces back to its original shape almost immediately after the aircraft moves on. This is known as *elastic* behavior.

However, if the aircraft parks on the ice for a period of time, the ice again will bend beneath its weight, but will not return to its original shape after the aircraft moves on. This is known as *plastic* behavior. Thus, ice can behave in different manners, depending on how rapidly a force is applied to it.

As the target of major study, sea ice has only come into its own within the past decade. But in these years, scientists from nearly a dozen different academic disciplines have made it a subject of high priority. What they have discovered is of significance far beyond the research laboratory.

By knowing all about the physical properties of arctic ice in all its various forms, as well as its dynamic qualities under just about every climate condition, engineers are able to design and build stationary structures that can resist ice pressures. In addition, they have invented sensitive instruments that measure changes in ice pressure and movement, permitting man for the first time to turn away the threat posed by ice on the move.

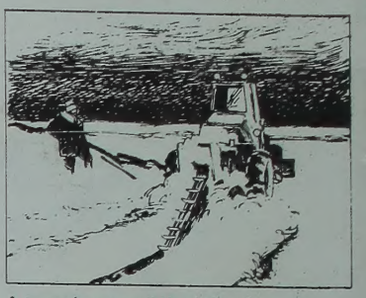
Those advances enable the petroleum industry to work in the arctic in safety, and without harm to the environment. To the direct benefit of the nation, much of the mystery is being lifted from the once-mysterious arctic.



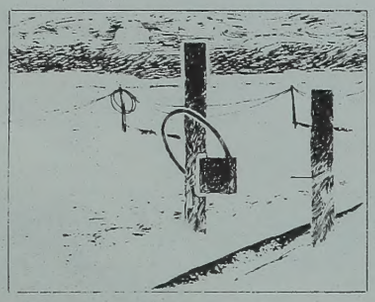

*Crystal structure of arctic sea ice changes with depth.*

# Profile of a Drill Site

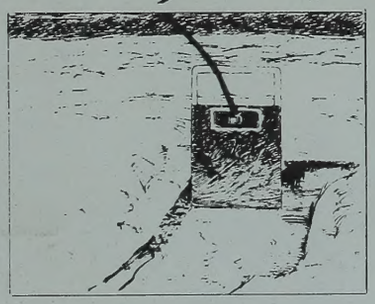
Fuel tanks are double-walled, and set in pits lined with thick plastic.



A trench around the island encourages ice failure.



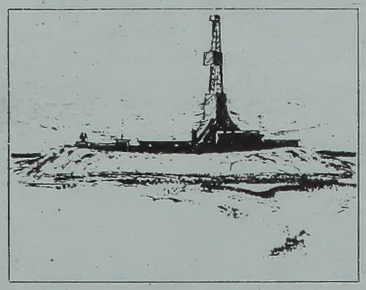
This sensor alerts rig of rapid ice movement.



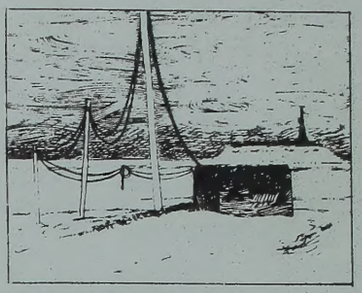
Pressure plates measure stress in the ice sheet.

Drilling superintendent monitors all ice reports.

*Larger than three football fields, Exxon's drilling islands are protected against sea ice by various combinations of active and passive defenses. Here's an example of a fully instrumented site.*



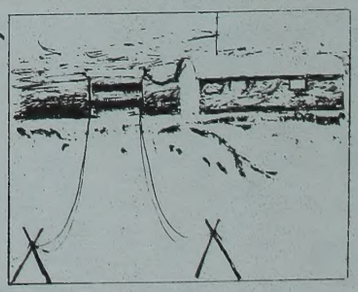
Drilling surface is sloped inward to contain leaks.



Inside this box, a bottom-anchored taut wire measures distance and direction of ice movement.

Eight-foot-long probes tell ice thickness and temperatures.

The island's steep sides resist ice override.



Cables connect all sensors to the technician's building.

Bulldozer is available to clear away ice rubble.

# On Solid Ground

In the winter of 1976, a significant climatic event occurred at an oil exploration island in the Beaufort Sea. The incident involved the island known as *Netserk North*, located in 23 feet of water in the Canadian Beaufort.

On February 6, 1976, an arctic storm of a severity that occurs perhaps only once in a hundred years, battered the drilling site. In less than eight hours, the four-foot-thick ice surrounding the island moved 350 feet.

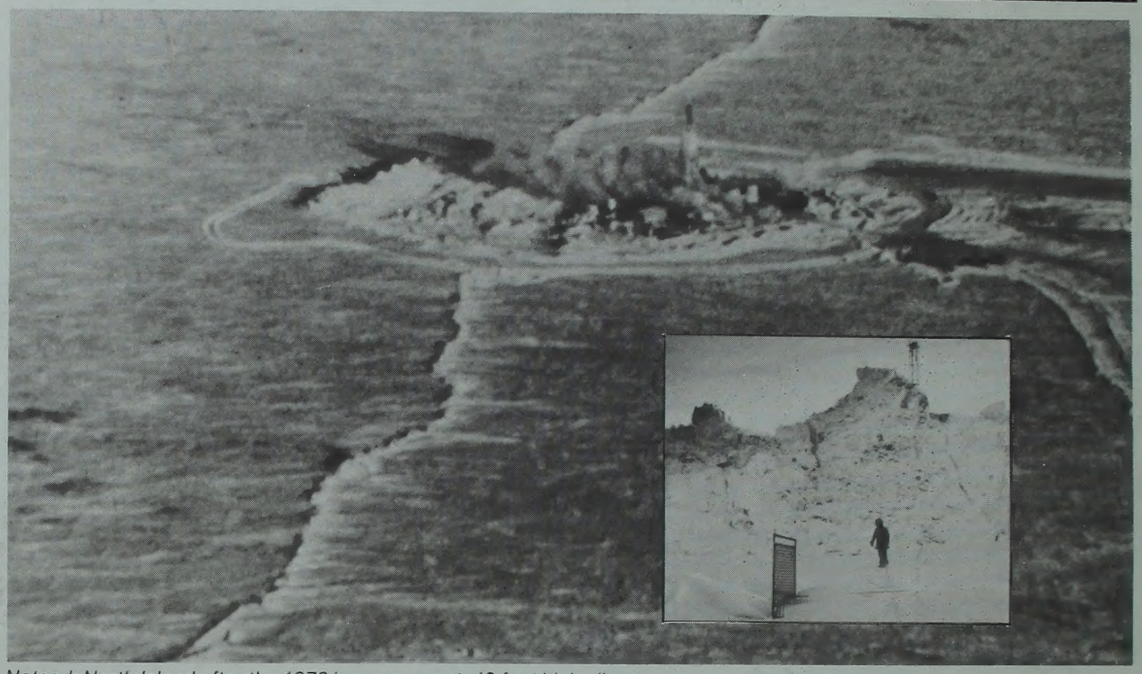
When the storm passed, researchers from Esso Resources Canada ventured onto the ice to survey the outcome. Clearly, this was a major test of the industry's claim that it had developed technology to handle major ice movements around its drilling islands.

What the workers found confirmed the industry's confidence. Four-foot thick sheets of ice had been deflected upward around the island. The ice-rubble field surrounding the island had grown from 20 to 40 feet tall. No ice encroached onto the island.

Of additional interest to ice scientists was a pressure ridge that had developed during the storm. Pressure ridges are, of course, one of nature's ways of dissipating the forces that build in moving ice. Quite simply, a pressure ridge absorbs the forces that push the ice sheet forward by diverting its motion in new directions—upward and downward—creating a rubble of ice blocks.

The pressure ridge that had developed during the storm followed a generally straight line for miles across the ice. On the north side of this line, the ice had pushed southward 350 feet. On the south side, the ice had hardly moved at all. This ridgeline had passed directly through the Netserk North location.

Had the old saying applied—that once the ice starts moving, nothing can stop it—much of Netserk North should have been under ice. Instead, a fascinating thing had happened at the island: the ridge through Netserk North assumed a distinct horseshoe shape around the island. And just as distinctly, it returned to its former straight line beyond the island.



*Netserk North Island after the 1976 ice movement: 40-foot high pile-up.*

The island itself was unaffected.

Oil industry officials were pleased that their rig and the drilling island at Netserk North came through the storm without damage, but they weren't really surprised. Studies, research, and tests had begun years before to develop methods of preventing damage to industry installations or to the environment.

The accumulation of that knowledge offers an intriguing study into the evolution of island technology. Begun in 1969, the research and experimentation grew into a body of information that, seven years later in 1976, could be used to successfully withstand the rigors of a major Arctic storm. The process was as deliberate as it was thorough.

# Two Kinds of Islands

One of the areas of early industry study was in the coastal waters of the Beaufort Sea bordering Alaska. The region is dotted by low-lying islands a few miles north of the coastline. Little more than bars of gravel or sand, these mounds of sediment are interspersed with large islands composed of arctic tundra left over from a time—centuries ago—before the coastline began sinking and retreating southward.

These tiny accumulations of mostly alluvial deposits are known as the Barrier Islands. Some of these islands literally drift with the tides—moving stone by stone and grain by grain—in response to the prevailing currents of summer. Still, these formations—the Midway Islands, McClure Islands, Stockton Islands, and others—play an important part in protecting the low-lying northern Alaska coastline from the effects of erosion by the Arctic Ocean.

In recent years, such naturally occuring gravel islands became objects of considerable curiosity to oil industry experts intent upon designing the safest, most practical drilling sites possible for the area. As rough models for the oil industry's drilling pads, the natural islands offered hints of what would happen at the industry's own drillsites. Drilling pads are, of course, basic to the task of determining if significant deposits of oil and gas are trapped beneath the Beaufort. Yet many of these natural islands showed clear evidence that ice routinely invaded their beaches during the winter.

Leavitt Island, northwest of Prudhoe Bay, is typical. A part of the Jones Islands group, Leavitt Island has a wide, flat beach which extends smoothly from the water's edge to the island's high point, four to five feet above sea level. Leavitt's gravel surface is barren of vegetation, and is heavily scarred on its seaward side—a testament to its many battles with the sea ice.

In contrast, Bodfish Island—just east of Leavitt—has little such scarring. But scientists saw that Bodfish is different. Its beaches end almost in the shadow of its shoreline, abruptly rising five to six feet. This blunt shape can be traced to the island's living cover of tundra vegetation—unlike Leavitt which is barren. In summer, Bodfish's tightly held sediments are undercut by storm waves—nature's guarantee that the stubby slope will endure.

Could it be that this difference of slope accounted for the variance in the way the two islands reacted to ice? Leavitt, with its shallow beaches, had little to obstruct an almost straight-line advance of moving ice. Bodfish, on the other hand, offered a steep obstruction. Ice pushing against its slope was forced upward, causing it to bend under stress and fall back upon itself.

Industry engineers were fully aware that ice would be one of the major problems they would face. A drilling site during its working life obviously would be threatened by

# Across The Boundary

While, in retrospect, the decision to use artificial islands was sound, at the time the engineers knew full well that their solution would require something more than just pitting an object of appropriate size and weight against the forces of sea ice.

There were other concerns; a number of other natural forces also had to be considered. Just as important as winter's ice invasions were summer's environmental hazards—storm surges, river flooding, and wave erosion. The extremes of a possible, once-in-a-hundred-year storm were as significant as year-in, year-out weather.

Ultimately, when the time came to refine their island designs to cope with these forces—ice in particular—the oil industry would take a lesson from the Oriental masters of judo and karate: they would seek to turn the power of the opponent to their own advantage.

Among the research facilities mobilized to help them do so was an ice basin built in Calgary, Canada, home of Esso Resources Canada, Ltd. Constructed in 1973, the basin is the world's largest such test facility, enabling scientists to create ice sheets and actually force them against test islands, among other structures, in order to study the interaction.

Such research, along with eyewitness accounts of actual ice overrides observed by scientists, confirmed the technical theory: if ice could be made to change direction sharply, it would thrust upward until it buckled naturally under its own weight. The scientists concluded that, in shorefast and transition ice zones, man-made islands could do the job.

In 1972, the pioneering work of actually designing and constructing an artificial island began. It too took place in the Canadian waters of the Beaufort, at a site known as *Immerk Island*. The construction technique was straightforward. After summer melting of the ice, construction crews dredged sand and gravel from the seabed near the drillsite. The resulting island, roughly 400 feet in diameter, was allowed to stand without a drilling rig through a full arctic winter, as a test of its ice-handling abilities.

The island experienced no difficulties, and with the understanding of ice behavior gained in subsequent years, this test no longer is used.

The first construction effort was in ten feet of water. But as it was determined that islands could be constructed effectively and safely, the push to deeper waters began. Other construction techniques were tried with different materials, including gravel trucked over the ice from shorebased locations, and silt dredged at the site. Some islands were protected with huge sandbags to resist summer erosion. Others were built with wide beaches around their perimeters. All were designed with an abiding respect and concern for the ice and sea.

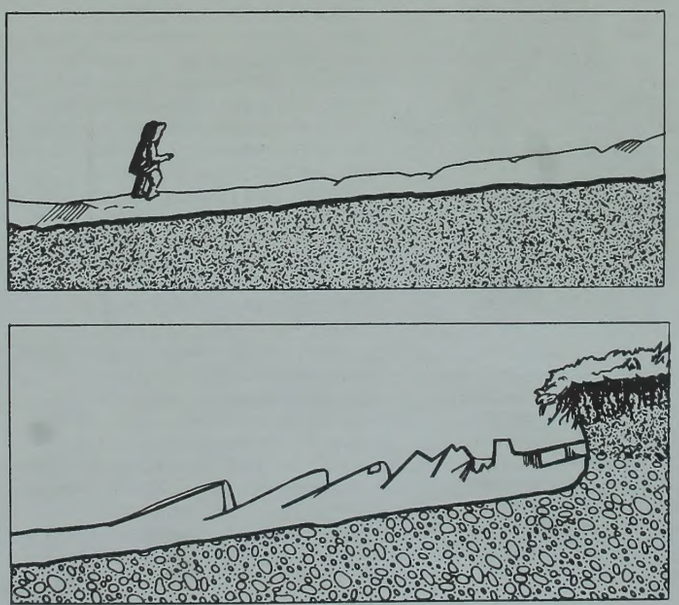
*Autumn ice buildup begins around Issungnak Island, located in 63 feet of water in the Canadian Beaufort.*

From that tentative start, Canadian operators moved into deeper waters, building one or two new islands each year. By 1979, Exxon's Canadian affiliate had completed a drilling site in 63 feet of water. Called *Issungnak*, it is one of 19 such exploratory sites constructed between 1972 and 1981 in the Canadian Beaufort, all successfully operated without harm to the environment. Currently, the water depth record is held by Dome Petroleum, Ltd., which recently constructed an island in about 80 feet of water for Gulf Canada.

advances of sea ice. It would have to resist—and resist successfully.

The idea of designing platforms from nature itself had appealing aspects. For one thing, artificial islands would look much like the natural ones that dot the Arctic coastline. Also, they could be made of the same materials, such as the abundant deposits of sand and gravel that have been swept down the tundra rivers from the Brooks Range, far inland.

Looking back now, experience confirms what observation and then detailed calculations had suggested: that man-made islands are a technically and economically attractive and safe way to carry out exploratory drilling in shallow Beaufort waters. Such islands can support year-round operations. At the same time, there is no evidence of significant impact on the environment. In fact, when drilling operations are completed and all equipment removed, nature itself reclaims the islands and reduces them in size. In some cases, they become potential breeding grounds for arctic wild fowl.



*Flat beaches vs. blunt shorelines — Clues from Nature.*

# Into U. S. Waters

As a result of the Canadian experience, in March, 1978, Exxon became one of three U.S. companies to go ahead with similar construction in the Alaskan Beaufort.

As a piece of real estate, the company's first island was 400 feet in diameter, put down in three and a half feet of water. Since that time, Exxon has constructed two other islands in Beaufort waters as deep as 20 feet. Six islands have been built by other oil companies in water depths up to 40 feet.

Exxon engineers named their first site *Duck Island*, after a natural island nearby. It was constructed in a protected area inside the Barrier Islands, just north of the point of the Alaska coast where the Sagavanirktok River empties into the Beaufort.

Among the 39 permits and major approvals needed for construction of the Duck Island pad was one permitting Exxon to excavate 75,000 cubic yards of gravel from a site 11 miles inland. The gravel was to be taken from five high areas along an inactive channel of the Sagavanirktok River—a shallow, rock-filled stream with channels braided together more than a mile wide across the tundra.

As a source of gravel, these sites were selected only after they had passed rigorous environmental tests. Would removal of the gravel endanger wildlife? Would it alter a habitat? Would it destroy a historic site, disturb a burial ground, ruin a traditional hunting area, or infringe upon a native land claim? The sites selected along the Sagavanirktok River were fully acceptable in each of these areas.

*Gravel deliveries to an Alaskan island construction site.*

Seabottom coring at the new drilling site indicated that the sea floor would settle only a few inches under the added weight of the gravel. But in order to truck the gravel from the riverbed to the pad, an *ice road* was needed—both to protect the vegetation on land, and to strengthen the ice of the crossing at sea.

On March 6, 1978, six giant-wheeled *Rolligons*, their balloon tires pressing down with only eight pounds of pressure per square inch, began pumping sea water on top of the existing ice. This froze to form the 11-mile-long road needed to support gravel-hauling and construction vehicles. By March 18, the road was sufficiently thick to permit construction of the pad to begin.

At the pad site, backhoes bit into the four-foot-thick sea ice. Bulldozers pushed the rubble 250 feet back from the widening hole—just far enough to keep it out of the way. Had the ice not been frozen to the sea bottom, a trenching machine would have sliced it into blocks so that flatbed trucks could carry it away.

Simultaneously with the start of ice excavation, removal of gravel from the river began. Only the topmost three feet of gravel resting above the normal waterline of the riverbed was selected for the operation. That way, no holes were created to snare animals or to entrap fish under the ice during the winter.

By April 5, 1978—one month after it began—the entire construction operation was finished. The new island—complete with a gently concave top to direct leaks, should they occur, toward its center, and a steep berm along its sides to divert ice away—was ready for its drilling rig.

Exxon successfully drilled two exploratory wells from this site over a two-year period, 1978 and 1979. In all, Alaska's oil companies have drilled 18 wells in the waters of the Alaskan Beaufort through 1982.

# Profile of a Rubble Field

*Researcher at a Canadian drill site's ice field.*

As part of the exploration effort in both Alaska and Canada, the action of ice on artificial islands has been carefully documented in order to gain a better understanding of ice behavior. Full-time monitoring personnel were stationed at selected drilling sites. Pressure and movement detectors, some of them especially designed by Exxon, were embedded in ice at distances of up to a mile from the island. In Alaska, an alarm system was developed to warn the drilling crew of pressure buildups or movement in the ice. In Canada, time-lapse cameras were set up to record the position of the ice every 15 minutes, both day and night.

From these efforts, scientists learned that in sheltered water depths of 10 feet or less, ice normally behaves much as it does on a lake: it quickly becomes solidly landfast after freezing, with only small expansions and contractions occurring thereafter under the stress of wind or thermal expansion.

The scientists also identified two different ways in which moving ice expends its energy when it pushes against an island. Early in the winter, it fails by *folding* upon itself—much like an accordian. Later in the winter, as its thickness increases, it fails by *crushing* or *grinding*, as one piece rubs against another.

Ice conditions in the Canadian Beaufort are similar to those that will be encountered in Alaskan waters beyond the barrier islands. Concentrating their attention on unsheltered waters deeper than 10 feet, Canadian scientists studied what would become known as the *rubble-pile effect*. Under storm conditions during early winter—October and November—the relatively thin, one-to-two-foot ice can move several thousand feet, causing extensive fields of ice rubble to form on the side of the island facing the storm. This rubble field freezes to the island's perimeter, and can actually become an important factor in the island's resistance against later movements of thicker ice. If a pileup does not naturally occur, workers may cut the ice in an effort to start one artificially. This precautionary trenching often begins when the ice reaches a thickness of about two feet.

Once started, the rubble pile continues to grow as winter deepens. In some cases, the previous rubble forms a ramp-like slope, and the oncoming ice-sheet advances up this slope until it is left without support to break under its own weight. At other times, the ice penetrates directly into the existing rubble, but again fractures and folds upon itself.

Below the surface, a similar pattern of ice disorder is occurring. Some of the upended ice-rafts tilt into the seafloor, grounding there for stability. Other pieces simply freeze into new relationships, increasing the rubble's mass.

Once a certain height is reached—perhaps on the order of 20 feet—the rubble pile tends to grow seaward. In the course of a winter, depending upon the amount of ice movement in the area, as much as 2,000 feet of ice rubble can collect and freeze against an island, adding to its defensive strength.

Eventually, as the winter continues, a change occurs in the way the ice around the island fails. It becomes too thick to bend, and begins to fail in *crushing*. An active crack develops at the outer edge of the rubble field. Inside this area, the ice stabilizes. Along the active outer crack, the ice grinds against the edge of the rubble for the remainder of the winter, much as it does naturally at the edge of the arctic ice pack. Only an extreme event, such as the 1976 storm at Netserk North, can cause the ice to revert to its former bending method of failure. But even then, a portion of the island's protection comes from its rubble fields—as Netserk demonstrated.

# The Active Measures

Intimate knowledge of the behavior of arctic ice under almost every possible climatic or atmospheric condition has permitted the industry to design custom-made islands for offshore petroleum exploration. Ideally, each such work site should be able to withstand ice advances with no active assistance.

But for Exxon, that's not always good enough. As exploration extends into deeper water, where operating experience may be limited, Exxon has developed an early warning system for use at certain locations. This system, which is called the *Island Ice Defense and Monitoring Network*, involves the use of sensitive electronic devices that warn of potentially hazardous ice conditions. When so alerted, island crews are prepared to take active steps to relieve a buildup of ice pressure.

The outer ring of this defense and monitoring network—the early warning stations, so to speak—involves two types of electronic systems. One employs ice *pressure sensors*—devices invented and patented by Exxon expressly for this purpose.

The Exxon ice pressure sensor is an all-metal device 18 inches wide and seven feet long—but less than one-half inch thick. The sensor consists of a "sandwich" of aluminum plates, separated by a specially designed "bending plate." This bending plate deforms when stress is applied.

Each sensor can measure and continuously signal the stress exerted upon it by the surrounding ice. In a typical gravel island installation, four to six such sensors are implanted in the ice in a circle out about 100 yards from the perimeter of the island. Cables from each unit feed directly back to an instrumentation building on the island. There the electrical signals are recorded day and night.

At the same time, several thousand feet away from the island, ice *movement indicators* are implanted in the ice. These tell whether the ice sheet is moving and, if so, its direction and speed. The impulses from these indicators are also fed directly and automatically to the computer in the island's instrumentation building.

These two electronic systems, then, can provide the island's drilling superintendent with precise information on the two most important details about the ice all around him: first, is it moving? And second, what sort of pressure is being exerted against his island?

Additionally, such devices as ice *temperature probes* are employed to determine ice thickness automatically. Other advanced devices such as surface radar can also be installed, if required, to monitor ice conditions out some distance from the island.

All data received from the electronic impulses are analyzed, and become part of the ice warning system. But what happens if unusual ice conditions are detected by the sensitive instruments? An established sequence of events takes place. At the sound of an automatic alarm, the drilling superintendent can send his crews into action to help nature along, in effect, by first relieving a pressure build-up.

*Slotting weakens the ice sheet, encouraging it to buckle.*

One way this is done is known as "slotting." This requires a ditching machine—the same kind used by construction companies to dig trenches for telephone cables or water pipe. It is driven out onto the ice. Then, using the machine's trenching boom, the operator cuts a slot eight inches wide into the ice.

The slotting immediately alters the ability of the ice to exert pressure against the island, by breaking down the solid contact that can exist between the ice and the island. Advancing ice will tend to break up and create a potentially beneficial ice pile-up.

As back-up for a full-time ice technician on the island, digitized records of the ice pressure, ice movement, and weather data can be transmitted to a shore station; and, when desired, from there to the Exxon Production Research Company in Houston, Texas.

There, other ice experts are in a position to observe with scientific accuracy what is happening on the arctic ice sheet around a man-made gravel island some 5,000 miles away. Should they detect any condition requiring countermeasures, they need only pick up the telephone to be in immediate contact with the drilling superintendent.

The Island Ice Defense and Monitoring Network described here will probably not be needed or utilized on all islands. It will be installed and utilized where the benefits appear justified; either for ice data research requirements or for operational needs.

To an outsider, a lonely drill rig on a tiny dot of land seems fragile as it lies low above the arctic ice—perhaps vulnerable to the harsh elements around it. Yet years of rigorous experience, combined with intensive research and engineering studies in both the laboratory and the field, have made islands and their equipment anything but helpless.

Work in the landfast ice areas of the Beaufort Sea has proven the soundness of the design and construction of the oil industry's man-made islands in shallow waters. The way has been cleared for arctic oil exploration and development in deeper waters, where the ice conditions will be more severe. Exxon is actively developing the technology that will enable this work to be carried out safely.

*Seven-foot long sensors send back continuous measurements of ice pressure.*

EXXON COMPANY, U.S.A.